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The potential of fission nuclear power in resolving global climate change under the constraints of nuclear fuel resources and once-through fuel cycles

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ABSTRACT

Nuclear fission is receiving new attention as a developed source of carbon-free energy. A much larger number of nuclear reactors would be needed for a major impact on carbon emission. The crucial question is whether it can be done without increasing the risk of nuclear proliferation. Specifically, can a larger nuclear share in world energy production, well above the present 6%, be achieved in the next few decades without adding the proliferation-sensitive technologies of reprocessing spent fuel and recycling plutonium to the problems of the unavoidable use of enrichment technology? The answer depends on the available uranium resources. We first looked for the maximum possible nuclear build-up in the 2025–2065 period under the constraints of the estimated uranium resources and the use of once-through nuclear fuel technology. Our results show that nuclear energy without reprocessing could reduce carbon emission by 39.6% of the total reduction needed to bring the WEO 2009 Reference Scenario prediction of total GHG emissions in 2065 to the level of the WEO 450 Scenario limiting global temperature increase to 2 °C. The less demanding strategy of the nuclear replacement of all non-CCS coal power plants retiring during the 2025–2065 period would reduce emission by 26.1%.

1. Introduction

To the question of whether nuclear energy under resource constraint can make a serious contribution to solving the climate problem, an easy answer can be offered. Current reactors essentially use the uranium isotope U^{235}, with an abundance of 0.7% in natural uranium. By using the energy of U^{238}, a much more abundant uranium isotope, nuclear energy would be practically inexhaustible, sufficient for the millennia. The first reactor able to do this, of the fast breeder type, was constructed in 1951. The concept and technology were developed in some 20 subsequent reactors, the largest being the Super-Fenix in France.[1] We are, of course, aware of the studies that look at the possible nuclear contribution with the early introduction of fast breeders, obligatory reprocessing of spent fuel and recycling of plutonium. It is not difficult to construct nuclear strategies employing breeder reactors reaching high shares of nuclear energy in total world energy production (Nifenecker et al., 2003), since then uranium resources would not be a limitation. Technically, such strategies are perfectly sound. However, many leading experts and analysts believe that the world is not ready for the large-scale reprocessing of the spent fuel and the large-scale use of plutonium (AAAS, 2009; MIT EI, 2009; ENS-HSC, 2010) required for the operation of fast breeders. Such a future, at least for a few decades, would pose an increased threat of nuclear proliferation and nuclear terrorism.[2] Abuses of enrichment technology are a large enough problem, which should not be multiplied. The use of low-enriched uranium in a large percentage of operating reactors cannot be avoided. In addition to IAEA safeguards, various ideas to prevent the abuse of national enrichment installations for the production of highly enriched uranium usable as nuclear explosives have been discussed. There have been several proposals to eliminate national enrichment installations by establishing an international

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[1] A fast breeder reactor, the Super-Fenix sodium-cooled pool-type reactor of 1200 MWe, was operated in France in the years 1986–1998. With a higher investment cost than water-cooled thermal reactors and the low price of uranium, it could not be economically competitive at the time.

[2] US President Barack Obama said the following in a speech delivered in Prague on April 5, 2009: "Today the Cold War has disappeared but thousands of those weapons have not. In a strange turn of history, the threat of nuclear war has gone down, but the risk of a nuclear attack has gone up. More nations have acquired those weapons. Testing has continued. Black market trade in nuclear secrets and nuclear materials abound. The technology to build a bomb has spread. Terrorists are determined to buy, build or steal one. Our efforts to contain these dangers are centered on a global non-proliferation regime, but as more people and nations break the rules, we could reach the point where the center cannot hold.""[W]e must ensure that terrorists never acquire a nuclear weapon. This is the most immediate and extreme threat to global security…. [T]oday I am announcing a new international effort to secure all vulnerable nuclear material around the world within four years."

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fuel bank. The current dispute with Iran may accelerate the finding of a generally acceptable solution in the spirit of the NPT accord. Unlike enriched uranium, plutonium is not required for the operation of current power reactors and the proliferation risk associated with spent fuel reprocessing installations can be avoided.[3] Plutonium use would increase uranium utilization but that can be postponed without economic loss until the uranium supply is running out or the price becomes much higher. It may be true that plutonium use need not add to the proliferation risk if applied in nuclear-weapon countries (NWC) only. However, these countries would not be isolated islands and the plutonium technology would spread. It is our firm view that the strengthening of the Nuclear Non-Proliferation Treaty (NPT), the Fissile Materials Cut-off Treaty and, finally, the removal and banning of nuclear weapons are prerequisites for proliferation-safe large-scale plutonium use. On the other hand, when the large-scale expansion of nuclear power without reprocessing and plutonium use is considered, uranium resources become a limiting factor (Pevec et al., 2008).

Thus, a relevant question addressed here is whether nuclear energy can make a serious contribution to the climate problem without going into the presently unacceptable large-scale use of plutonium, i.e., without fuel reprocessing, using only more controllable once-through fuel technology, which essentially only burns U^{235}.

Whether once-through technology can support the large-scale expansion of nuclear power is a question of nuclear fuel resources. The sufficiency of nuclear fuel for long-term use and the expansion of nuclear power have been discussed by individual analysts and institutions, with a wide spectrum of answers corresponding to the variety of the initial assumptions on uranium resources, reactor technologies and energy strategies. With suitable choices of assumptions, arguments have occasionally been constructed for the claim that nuclear power has no long-term future due to inadequate fuel resources. Conversely, again with appropriate choices of assumptions, reassuringly long times of nuclear fuel availability have been obtained, even with an inefficient once-through open nuclear fuel cycle. Typical scenarios assume an extension of the present slow growth of nuclear power or a constant share of nuclear power in total world energy production, now slightly above 6%. With once-through fuel cycles, resources may last well over a hundred years, as will be shown subsequently. The argument continues that by then we shall have nuclear fusion, so there is no reason for concern about nuclear fuel. In the current state of world affairs, we cannot afford the comfort of such reasoning as it neglects the potential of nuclear energy to make a major contribution to the solution of potentially crucial problems facing humanity: how to stop the climate changes threatening our civilization and how to do so in time. Unlike various alternative non-CO_2-emitting energy sources, fission energy is technically developed and available now, as witnessed by 436 reactors in operation and some 14,000 reactor-years of experience.

2. The climate problem is shaping future energy strategies

Leading world climatologists are asking for immediate measures in order to escape the critical 2 °C temperature rise limit, after which climate changes beyond human control are feared (IPCC, 2007; UN, 2007; IEA, 2009; EEA, 2008). This temperature rise limit was adopted in the Copenhagen Accord at the UN Framework Conference on Climate Change in December 2009 (UNFCCC, 2009) and by the European Community (EU, 2007, 2010). The recommendation by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report is a 50% reduction in emission by 2050. Faced with such a gigantic task, questioning IPCC predictions is perfectly legitimate. They are not and cannot be definite. Climate modeling is a scientific process in development; new and better data will fill the gaps in the picture. However, to wait until all the details are resolved would not be prudent policy in view of the nature of the physical and chemical processes, which with several positive feedbacks may escape control if the average world temperature increases by more than 2 °C. A drastic reversal of “business as usual” in energy development is required. According to a report by the International Energy Agency (IEA), WEO 2009 Reference Scenario (IEA, 2009), by continuing present trends, global greenhouse-gases (GHG) emission from all sectors would reach 56.5 $GtCO_2$-eq by 2030 and 68.4 $GtCO_2$-eq by 2050, increasing from 42.4 $GtCO_2$-eq in 2005. Continuation of this trend would increase long-term CO_2-eq concentration in excess of 1000 ppm and increase average temperature by up to 6 °C, leading almost certainly to irreparable damage to the planet. The environmentally sustainable WEO 450 Energy Strategy, in line with the Copenhagen Accord and EU energy policy but much more demanding, aims to stabilize concentration at 450 ppm and limit temperature increase to 2 °C. In WEO 2009, strong arguments are presented for this scenario of future development. The estimated limit on total GHG emission in 2030 would be 37.1 and 21 $GtCO_2$-eq in 2050,[4] which is below the 2005 level (42.4 Gt) and 47.4 Gt below the reference scenario. The time scale appears to be too short for several non-CO_2-emitting technologies. Carbon capture and storage (CCS) technology is in the development stage for future applications, which will have to grow from the present experimental level of million tons per year to a billion tons per year scale. Many safe no-leakage storage locations would be required. The future success of applications on such a scale cannot be taken for granted.

No solution can be seen in nuclear fusion, either. Even should the tokamak concept of nuclear fusion develop successfully, which is by no means certain, a significant contribution by nuclear fusion to world energy production cannot be expected before 2070. This is evident from the dynamics of ITER and follow-up projects. Plasma ignition may be achieved at the laser fusion National Ignition Facility of Lawrence Livermore National Laboratory (LLNL) this year but the technological problems are so formidable that the prediction cannot be more optimistic.[5] In spite of the potential of solar energy, requiring two or three decades to achieve economic competitiveness (Zweibel et al., 2008), it is less ready for large-scale deployment than wind energy (GWEC, 2006). However, even when renewable sources of energy, such as wind and solar, become technically and economically ready for large-scale deployment, the intermittent nature of their energy production would limit their share in total energy production, barring the development of energy storage at an acceptable cost. At the same time, nuclear energy, with a share of only 6% in total energy production, is not making an essential contribution to the production of non-CO_2 emitting energy. With such an outlook, we think it worthwhile to evaluate the potential of nuclear fission to assume a considerably larger share in energy

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[3] The low enriched uranium (enrichment level from 3% to 10%) needed as power reactor fuel cannot be used as a nuclear explosive. Unlike plutonium, the uranium 235 in reactor fuel cannot be separated from uranium 238 by chemical methods. The presently stalled Fissile Materials Cutoff Treaty, FMCT, would have an important role in preventing the production of higher enrichment by placing an upper limit on fuel enrichment. An international supply of enriched uranium for reactor use open to all NPT parties could be a part of front-end fuel cycle control. The FMCT plus the Comprehensive Test Ban Treaty in force would give a great boost to the NPT regime.

[4] Energy-related CO_2 emission amounts to about 84% of global CO_2 emission and about 64% of world GHG emission (IEA, 2009, p.168).

[5] Discussion of the technological problems of laser fusion can be found in the March 2010 issue of Scientific American.

production, under the constraints of limited uranium resources and without increasing proliferation risks by using only a once-through fuel cycle.

3. Aims and limits of the study

In this study, we consider the period to the year 2065 critical from the climate point of view, during which large contributions from CCS and fusion are not likely, while a large build-up of nuclear fission energy could be accomplished. There is nothing absolute regarding our selection of the year 2065 as the final year for this nuclear energy build-up. If the aim is to reduce carbon emissions, it should be as soon as possible, while other non-carbon sources are still not yet available on a large scale. The year 2065 is a present judgment, i.e., a compromise between what is desirable and what appears technically feasible, regardless of current limited nuclear plans. Strategies that would reach a high nuclear share later, by 2080 or 2100, would, of course, provide more time for the development of the technical and political prerequisites but their contribution to the urgent problem of CO_2 emission would be diminished or too late, if we take the IPCC recommendations seriously. The next few years will tell us whether we can afford delays. On the other hand, should the climate situation develop in an alarming way, demanding urgent measures and an earlier contribution of carbon-free energy, the final year of nuclear build-up could be moved back to about the year 2060, or even earlier. That would, of course, increase the annual reactor construction rate. The constraints would be in the industrial and economic capabilities. Therefore, we do not foresee that a large nuclear build-up could start before 2025. Having selected the nuclear build-up period of 2025–2065, we are investigating whether nuclear fission energy under the constraints of the estimated uranium resources and once-through nuclear technology in that critical period will be able to provide a share in total energy production much greater than the present 6%, which is insufficient to produce a major impact on the climate problem. With this aim, we are seeking the upper limit of the nuclear contribution requiring nuclear build-up, such as would consume the currently estimated uranium resources by 2065, using once-through fuel technology. We do not foresee the amounts required by once-through fuelling after 2065 for the reactors that do not end their operating lives by that year. By the year 2065, all the currently estimated uranium reserves will have been consumed or in reactors. What happens to the operations of reactors after that year is discussed later. If the upper limit of the nuclear contribution is of a magnitude that can essentially help reduce CO_2, we may then conclude that the reprocessing of spent fuel with its associated problems can be postponed until at least 2060. We would consider an essential nuclear contribution to be one that could, together with other carbon-free sources, lead to the fulfillment of the request in the WEO 450 Energy Strategy aimed at limiting global temperature increase to below 2 °C and the IPCC request to reduce CO_2 emission by 50% by 2050. In this paper, we do not consider the technical, financial or industrial challenges of nuclear build-up in any detail, in the belief that it is of primary importance to know whether an essential nuclear contribution under a given constraint is possible. We are perfectly aware that a nuclear build-up that would multiply the present nuclear share in total energy production is impossible before people in the major carbon emitting countries understand the urgent threat and act accordingly. Things may have to become worse before they improve. Only then could the presently unacceptable technical and financial challenges be seriously considered. Undoubtedly, nuclear build-up will be easier to accept if it is not necessarily accompanied by the recycling of plutonium. In order to determine whether a major nuclear contribution would be possible under the given resource and fuel cycle limitations, we do not argue for any specific nuclear development strategy based on current conditions and tendencies. A major nuclear contribution would still leave a giant space and challenge for other non-CO_2 emitting sources and technologies, none of which would be limited by the nuclear contribution. Quite the opposite, a strong nuclear contribution would give them more time for development. Furthermore, a large share of carbon-free nuclear energy by or before 2065, covering the base load in the energy network, could support the operation of intermittent sources, such as solar and wind, before economical energy storage technologies or very large advanced electricity grids are developed.

4. Uranium and thorium resources

4.1. Conventional uranium resources

A joint report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency published in 2008 (OECD/NEA-IAEA, 2008) categorizes uranium resources into identified resources (corresponding to the previous known conventional resources) and undiscovered resources. Identified resources consist of reasonably assured resources (RAR) and inferred resources. Undiscovered resources include Prognosticated Resources and Speculative Resources. Identified Resources amount to 5.469 million tons (3.338 million tons of RAR and 2.131 million tons of Inferred Resources). Undiscovered Resources amount to 10.5 million tons (2.77 million tons of Prognosticated Resources and 7.77 million tons of Speculative Resources). These estimates refer to uranium recoverable at a cost of less than 130 USD/kg. The total conventional resources amount to 16.009 million tons.

4.2. Unconventional uranium resources (Barthel, 2005)

4.2.1. Phosphate deposits

At a higher cost, uranium can be extracted from phosphate deposits. Uranium contained in phosphate deposits is estimated at 22 million tons, although annual production is limited by annual phosphoric acid production. The upper limit is below 10,000 t/year, so even if all the phosphoric acid production were considered, the total addition would not exceed one million tons. The historical operating costs for uranium recovery from phosphoric acid range from 60 to 140 USD/kg U (WISE, 2009). Recently, a new process (PhosEnergy) is being developed by Uranium Equities Limited, offering uranium recovery costs in the range from 65 to 80 USD/kg U. It is expected to be in commercial use in 2011 (WNA, 2009). However, should uranium extraction decoupled from phosphoric acid production cost less than 200 USD/kg U, an abundant addition to conventional resources would become available.

We do not assume that this will happen much sooner than 2060 and, thus, base our considerations on estimated conventional resources.

4.2.2. Uranium from seawater

The uranium concentration in seawater is only 0.003 ppm, yet it can be extracted. Research in this direction has been going for a long time. The cost of extraction from seawater can be regarded as the upper limit of the cost of uranium. The quantity of uranium in the sea is about 4 billion tons, exceeding any possible needs for thousands of years.

Japanese research on uranium recovery from seawater conducted between 2001 and 2006 estimated an extraction cost as low as 250 USD/kg U, which is more than twice as high as the present spot market price (Tamada et al., 2006). Although this price appears high, and certainly is, it could be acceptable for fast breeders with a closed fuel cycle.

4.3. *Thorium resources (Barthel, 2005)*

Thorium, as well as uranium, can be used as a nuclear fuel. Although the thorium isotope, Th^{232}, is not fissile, it can be converted into a fissile isotope of uranium, U^{233}, by slow neutrons absorption. The total world thorium resources, irrespective of economic availability, are presently estimated at about 6 million tons. The thorium resources recoverable at a cost lower than 80 USD/kg are estimated at 4.5 million tons. The identified thorium resources amount to 2 million tons and the prognosticated thorium resources amount to 2.5 million tons. Since thorium is not used in current nuclear reactors, we did not take thorium resources into account in our study.

5. Selection of nuclear energy development strategies

In all the development strategies, once-through fuel technology is used. Spent fuel is assumed to be stored in spent fuel casks on controlled sites, reserving the possibility of future reprocessing after 2060, if and when the conditions of proliferation safety will be established. The beginning year for all the development strategies is 2008.

5.1. *Low growth scenario (Scenario 1)*

A scenario of low nuclear capacity growth is a typical scenario, showing that resources are not a limiting factor for the small share of nuclear energy in total world energy production. This scenario has a moderate continuous growth strategy of 1.3% per year, as in the WEO 2009 Reference Scenario up to 2030. It would maintain the share of nuclear energy in total energy production.

5.2. *High growth scenarios (Scenarios 2 and 3)*

High growth scenarios are determined by asking for the maximum nuclear build-up that can be achieved by 2065, compatible with the present estimate of uranium resources and their use with once-through nuclear technology, i.e., without reprocessing. After 2065, there would be no more fresh uranium for once-through technology. The two scenarios differ in growth dynamics. Scenario 2 uses exponential growth from 2025, with the growth rate determined by the request for the consumption of the estimated resources by 2065. The second high growth strategy, Scenario 3, is characterized by linear growth, also starting with the year 2025 and continuing to 2065. Linear growth is assumed for the larger contributions in earlier years. Annual growth is again determined by the maximum growth possible with uranium resources lasting until 2065.

The selection of the initial year, 2025, for rapid build-up is based on the present state of the nuclear industry, large lead times and the time needed to prepare such an unprecedented undertaking. For the initial nuclear power levels in 2025, we take 459 GW using the WEO 2009 nuclear power and electricity production prediction for that year. We assume the linear increase of the energy availability factor in the 2025–2065 period from 0.88 to 0.90, extrapolating the trend from the earlier years.[6] In all the scenarios, we assume fuel consumption per unit energy produced that is typical for Generation 3 or Generation 3+ reactors, which will operate until Generation 4 reactors are commercialized. This may overstate actual consumption. Reduction could take place in conventional reactors but also through the introduction of some Generation 4 reactors. It is impossible at present to estimate with precision the effects of future developments on specific uranium consumption during the 2025–2065 period. However, to determine the sensitivity of the maximum build-up growth rates to specific consumption, we also looked into the strategies with specific consumption reduced by 10% and 20%, as variants of reference Scenario 3. Possible, even probable, reductions of specific uranium consumption would postpone the "exhaustion year," thereby strengthening conclusions about the sufficiency of reserves until 2065 without the reprocessing of spent fuel.

5.3. *An intermediate strategy, the replacement of non-CCS coal plants (Scenario 4)*

Analysis of high growth scenarios provides information about the maximum growth possible under the constraints of resources and fuel cycles, quantifying the largest possible impact on carbon emission. In order to see whether a less demanding nuclear build-up could still have a significant impact on carbon emission, we consider an intermediate strategy, Scenario 4. Our selection, as an illustration of what can be achieved, is a strategy that would replace all non-CCS coal power plants (CPP) with NPP during the 2025–2065 period. It is assumed that all new CPP after 2025 would have CCS installations.

In order to quantify the strategy, we select the linear dynamics of these replacements over the 2025–2065 period. Precise dates of replacements are impossible to foresee, while planned plant lifetime can be changed for technical or other reasons. It would be neither rational nor necessary to try to bind the exact dates of coal plant retirements to the operation starts of NPP. Linear nuclear build-up would start in the year 2025, again from the level predicted by the WEO 2009 for this year (459 GW). The impact reached by the year 2065 will essentially depend on the total power of the replaced CPP and much less on deviation from an even distribution of retirements over the 2025–2065 period. According to the WEO 2009, electricity production from CPP in the 2025 would amount to 13,387 TWh.

To produce the same amount of energy in NPP in 2025, the required net installed power would be 1736 GW, taking the value used in WEO 2009 for that year, 2025, for the energy availability of NPP. We could expect an increase in energy availability from 0.88 in 2025 to about 0.90 by 2065. The corresponding reduction of the required nuclear replacement power would probably be offset by the expected parallel increase in CPP efficiency, increasing the power to replace. Any precise predictions of trends are impossible, so we determine the required total nuclear replacement power, assuming energy availability factors to be constant in the 2025–2065 period for both nuclear and coal power plants.

Consequently, assuming a linear nuclear build-up strategy, average annual construction of 43.4 GW would be required throughout the 2025–2065 period. The total installed nuclear power by the year 2065 would amount to 2195 GW, assuming that the nuclear power plants in operation in 2025, as predicted 459 GW, will operate until 2065, or else be replaced if they have to retire. Installed power, uranium requirements and plutonium

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[6] The energy availability factor for 2025 was obtained from energy data in WEO 2009, Annex 1.

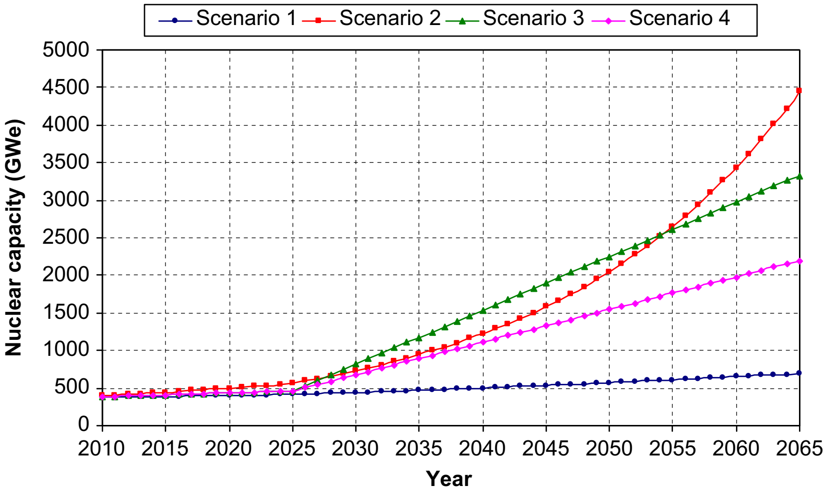

Fig. 1. The nuclear generating capacity for all four scenarios to the year 2065.

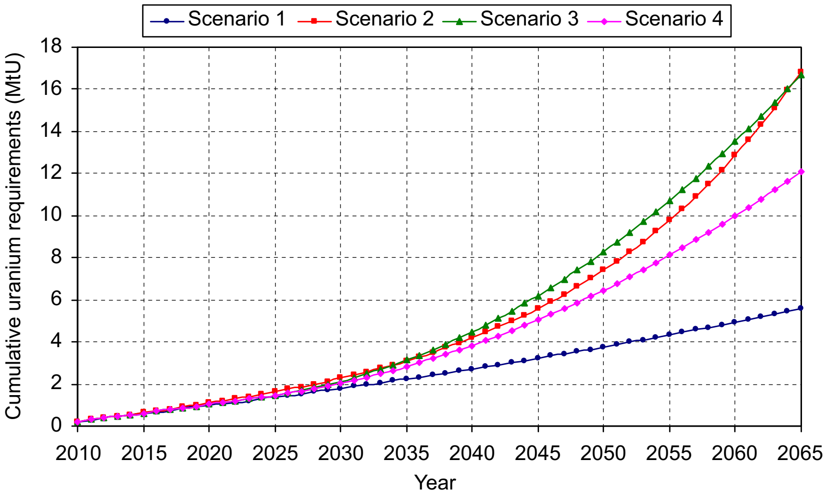

Fig. 2. The cumulative uranium requirements for all four scenarios to the year 2065.

production for this strategy are shown in Figs. 1 and 2, while Table 4 presents the annual and cumulative uranium requirements and plutonium production.

6. Maximum growth rates, uranium requirements and plutonium production

While the annual growth rate of 1.3% for Scenario 1 was adopted from the WEO 2009 Reference Scenario, the growth rates of Scenarios 2 and 3 were taken as variables to be determined, assuming that currently estimated conventional uranium resources would be consumed by the year 2065. The growth rates obtained this way are thus the largest possible under the constraints of uranium resources and once-through fuel technology. For exponential strategy Scenario 2, we obtain maximum annual growth of 5.3% after the year 2025, while for linear growth, Scenario 3, the maximum constant growth rate in the 2025–2065 period is 71.8 GW/year. The growth of nuclear capacities for all four strategies is presented in Fig. 1.

For all four scenarios, we calculated the annual uranium requirements and the cumulative uranium requirements, as well as the annual plutonium production and the cumulative plutonium production with the assumption of a once-through fuel cycle. The results obtained are presented in Table 1 for the low-growth scenario, Table 2 for the high-growth Scenario 2 (exponential case), Table 3 for the high-growth Scenario 3 (linear case) and Table 4 for intermediate Scenario 4. The cumulative uranium requirements as a function of time to the year 2065 for all four scenarios are presented in Fig. 2. For the low growth scenario, we obtained a draining-out time period for the currently estimated conventional uranium resources of 112 years. In both the high growth scenarios, the currently estimated conventional uranium resources would be exhausted by the year 2065, providing, as in the first scenario, that most of the currently estimated Undiscovered Conventional Uranium Resources have been turned into Identified categories by then.

7. Discussion of results

7.1. Low growth strategy

The Scenario 1 draining-out time period for the current estimate of conventional uranium resources shows that even with inefficient fuel use, uranium resources are not a limiting factor for projections of low and moderate nuclear capacity growth, which is nothing new. The cumulative uranium

Table 1
The nuclear capacity, annual uranium requirements, cumulative uranium requirements, annual plutonium production and cumulative plutonium production for the low-growth scenario to the year 2119 (year of draining out for conventional uranium resources).

Year	Nuclear capacity (GWe)	Annual uranium requirements (ktU)	Cumulative uranium requirements (MtU)	Annual plutonium production (tPu)	Cumulative plutonium production (tPu)
2008	373.2	72.5	0.07	55.9	55.9
2010	377.7	73.3	0.22	56.7	168.9
2020	401.0	77.9	0.98	60.2	754.6
2030	440.7	85.6	1.79	66.1	1382.9
2040	501.5	97.4	2.71	75.2	2093.2
2050	570.7	110.8	3.76	85.6	2901.4
2060	649.3	126.1	4.95	97.4	3821.1
2070	738.9	143.5	6.30	110.8	4867.5
2080	840.7	163.2	7.84	126.1	6058.2
2090	956.7	185.7	9.59	143.5	7413.1
2100	1088.5	211.3	11.59	163.3	8954.8
2110	1238.6	240.5	13.86	185.8	10,709.0
2119	1391.3	270.1	16.17	208.7	12,493.7

Table 2
The nuclear capacity, annual uranium requirements, cumulative uranium requirements, annual plutonium production and cumulative plutonium production for the high-growth Scenario 2 (exponential case) to the year 2065.

Year	Nuclear capacity (GWe)	Annual uranium requirements (ktU)	Cumulative uranium requirements (MtU)	Annual plutonium production (tPu)	Cumulative plutonium production (tPu)
2008	379.7	73.7	0.07	56.9	56.9
2010	397.8	77.2	0.23	59.7	174.9
2015	446.8	86.7	0.64	67.0	494.9
2020	501.8	97.4	1.11	75.3	854.4
2025	563.6	109.4	1.63	84.5	1258.1
2030	729.6	142.1	2.27	109.4	1752.9
2035	944.6	184.4	3.10	141.7	2393.6
2040	1222.9	239.4	4.18	183.4	3222.9
2045	1583.2	310.9	5.59	237.5	4296.6
2050	2049.6	403.6	7.41	307.4	5686.7
2055	2653.4	523.9	9.78	398.0	7486.2
2060	3435.2	680.2	12.85	515.3	9815.9
2065	4447.2	883.0	16.84	667.1	12,832.1

Table 3
The nuclear capacity, annual uranium requirements, cumulative uranium requirements, annual plutonium production and cumulative plutonium production for the high-growth Scenario 3 (linear case) to the year 2065.

Year	Nuclear capacity (GWe)	Annual uranium requirements (ktU)	Cumulative uranium requirements (MtU)	Annual plutonium production (tPu)	Cumulative plutonium production (tPu)
2008	375.9	72.9	0.07	56.4	56.38
2010	385.7	74.9	0.22	57.9	171.4
2015	410.1	79.6	0.61	61.5	471.6
2020	434.6	84.4	1.02	65.2	790.2
2025	459.0	89.1	1.46	68.9	1127.1
2030	817.9	159.2	2.11	122.7	1632.8
2035	1176.8	229.8	3.12	176.5	2407.7
2040	1535.6	300.7	4.48	230.3	3451.8
2045	1894.5	371.9	6.20	284.2	4765.0
2050	2253.4	443.7	8.28	338.0	6347.4
2055	2612.3	515.8	10.71	391.8	8198.9
2060	2971.1	588.3	13.51	445.7	10,319.6
2065	3330.0	661.2	16.67	499.5	12,709.4

requirements for this scenario would reach the amount of 16 million tons (the sum total of the currently estimated Identified Resources, Prognosticated Resources and Speculative Resources) by the year 2119, leaving enough time to turn most of the currently estimated Prognosticated and Speculative Resources into Identified ones. By the year 2119, installed nuclear power would reach 1391 GW. Nonetheless, we must emphasize that these nuclear capacity projections would not contribute significantly to the reduction of CO_2 emissions.

7.2. *High growth strategies*

We now proceed to consider the high-growth nuclear energy strategies that would consume currently estimated conventional uranium resources by 2065. For Scenario 2, we obtained a maximum annual growth rate of 5.3% for the 2025–2065 period, while the installed nuclear power in 2065 would reach 4447 GW. In Scenario 3, with linear growth, we obtained annual increases after 2025 of 71.8 GW, reaching an installed power of 3330 GW by

Table 4
The nuclear capacity, annual uranium requirements, cumulative uranium requirements, annual plutonium production and cumulative plutonium production for the intermediate growth Scenario 4 to the year 2065.

Year	Nuclear capacity (GWe)	Annual uranium requirements (ktU)	Cumulative uranium requirements (MtU)	Annual plutonium production (tPu)	Cumulative plutonium production (tPu)
2008	375.9	72.9	0.07	56.4	56.4
2010	385.7	74.9	0.22	57.9	171.4
2015	410.1	79.6	0.61	61.5	471.6
2020	434.6	84.4	1.02	65.2	790.2
2025	459.0	89.1	1.46	68.9	1127.1
2030	676.0	131.6	2.03	101.4	1569.0
2035	893.0	174.4	2.82	133.9	2173.7
2040	1110.0	217.3	3.82	166.5	2941.1
2045	1327.0	260.6	5.04	199.1	3871.2
2050	1544.0	304.0	6.47	231.6	4964.1
2055	1761.0	347.7	8.12	264.2	6219.8
2060	1978.0	391.7	9.99	296.7	7638.2
2065	2195.0	435.8	12.08	329.3	9219.3

2065. Annual uranium consumption by 2065 in our basic Scenario 3 would then reach about 661,000 t, and rather more in Scenario 2, about 883,000 t, while in both cases cumulative consumption would reach 16 million tons by the year 2065, i.e., exhaustion of the currently estimated uranium resources. As the nuclear build-ups continue until resource exhaustion, the obtained annual growth of 5.3% in Scenario 2 and the annual build-up of 71.8 GW in Scenario 3 are the largest nuclear build-ups that can be covered by consuming uranium resources until 2065 with once-through technology. With 10% more efficient use of uranium, there would be approximately 3 more years before exhaustion occurs. This shift is of interest primarily as a measure of the sensitivity of the assumed uranium consumption per unit of energy produced and the saved uranium can be considered as a reserve. Such saving could be possible with the improved efficiency of present reactors or by the introduction of advanced types. For our intended purpose, we do not think it necessary to go into the details of possible developments.

7.3. The impact of nuclear build-up on carbon emission, high-growth strategies

The important question, which can be answered now in a quantitative way, is about the nuclear contribution to total energy production, about the effect on global CO_2 emission in 2065. For this purpose, we select Scenario 3 with nuclear build-up to 3330 GW for detailed consideration. We afforded it preference because, as with smaller installed power and correspondingly smaller investments, its accumulated CO_2 emission saving is the same as with the 4447 GW Scenario 2 and it occurs earlier. Due to the exponential growth in Scenario 2, almost 50% of the carbon emission saving occurs in the last 10 years of operation, in the years 2055–2065, while for linear growth strategy (Scenario 3), 50% of the carbon saving occurs in the last 15 years, i.e., in the years 2050–2065. Thus, the linear strategy is more useful for CO_2 emission reduction and requires smaller total investments, albeit it is more demanding in the early stages of build-up. Quantification of the nuclear contribution in 2065 cannot be performed with complete certainty as there are no growth projections up to that year. In order to judge the impact of 3330 GW of carbon-free power, respectively 26,254 TWh[7] of carbon free nuclear energy in 2065, we can only make educated guesses about carbon emission in the year 2065 in comparison to the expected nuclear emission savings. Nuclear build-up would be best used to replace the worst carbon emitters, i.e., coal power plants emitting an average of 0.960 kg CO_2/kWh, so that nuclear energy replacing coal power plants would save emissions of 25.2 Gt of CO_2 in 2065.

The "Business-as-Usual" WEO 2009 Reference Scenario gives the energy-related carbon emission of 40.2 $GtCO_2$ for 2030, while total anthropogenic GHG emission would reach 56.5 Gt CO_2-eq. The total anthropogenic GHG emission according to the Reference Scenario for 2050 is 68.4 $GtCO_2$-eq. For the year 2065, we must perform extrapolation. Continuing to 2065 with linear extrapolation from the 2030–2050 period, total anthropogenic GHG emission in 2065 would reach 77.3 Gt CO_2-eq. With nuclear saving of 25.2 $GtCO_2$, where would the world be relative to the target level of the WEO 450 Scenario in 2065?

To extrapolate the total anthropogenic GHG emission of 21 $GtCO_2$-eq in 2050 to the year 2065 from WEO 450, we continue with the rate of decline between 2030 and 2050 from 37.1 to 21 Gt, into the 2050–2065 period. The extrapolated total anthropogenic GHG emission for 2065 then comes to 13.7 $GtCO_2$-eq. To reduce emission from the Reference Scenario level 77.3 $GtCO_2$-eq to the WEO 450 Scenario level of 13.7 $GtCO_2$-eq, an emission reduction of 63.6 $GtCO_2$ would be needed. Nuclear reduction of 25.2 $GtCO_2$ amounts to 39.6% of this requirement. Reduction of the remaining 38.4 $GtCO_2$, respectively, 60.4%, would be a future task in the development of carbon-free energy sources and energy efficiency, plus savings in all forms of energy use plus reduction in non-energy emissions. Undoubtedly, with nuclear reduction of greater than one-third, reduction of the remaining two thirds would be much easier to achieve. The relationships are shown in Fig. 3.

Linear nuclear build-up to a total of 3330 GW is the maximum under the defined constraints. A smaller nuclear contribution could be selected, with correspondingly increased contributions from alternative sources and emission reduction measures. The optimum mixture could only result from a much more complex study, which is impossible at present. As an example, a strategy that would end construction of new non-CSS coal plants by 2025 and replace all non-CCS coal power plants when they retire with nuclear power plants, our Scenario 4, would be well within the constraints of this study, as evident in Table 4.

7.4. Impact on carbon emission, intermediate strategy

We assess the impact of the intermediate strategy at the end of the replacement period, i.e., in the year 2065, again with reference

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[7] For the energy availability factor we take 0.90, extrapolating it from earlier years as given in the WEO 2009, p. 623.

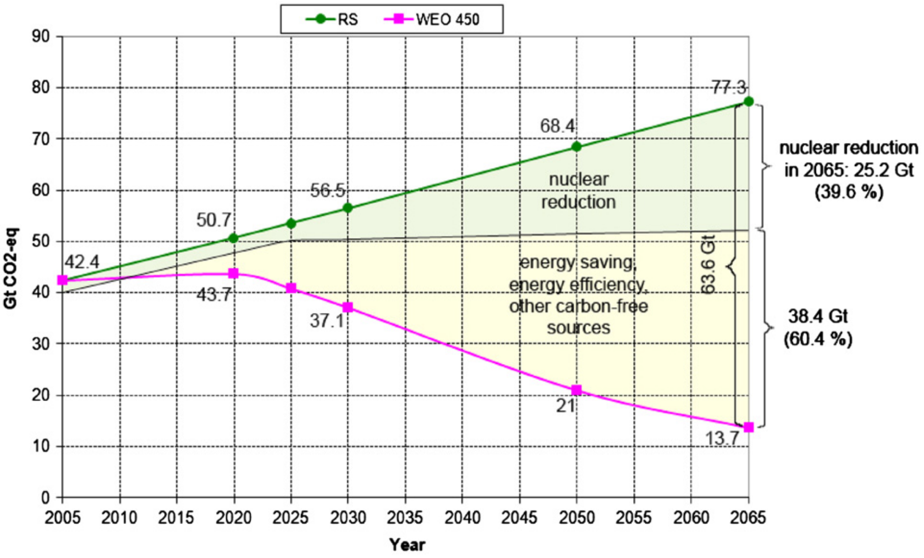

Fig. 3. Emission reduction by nuclear build-up (linear growth Scenario 3) in $GtCO_2$. The upper and bottom curves are the total anthropogenic emissions according the WEO 2009 Reference Scenario and the WEO 450 Scenario. The 2065 values were extrapolated from predictions for up to 2050.

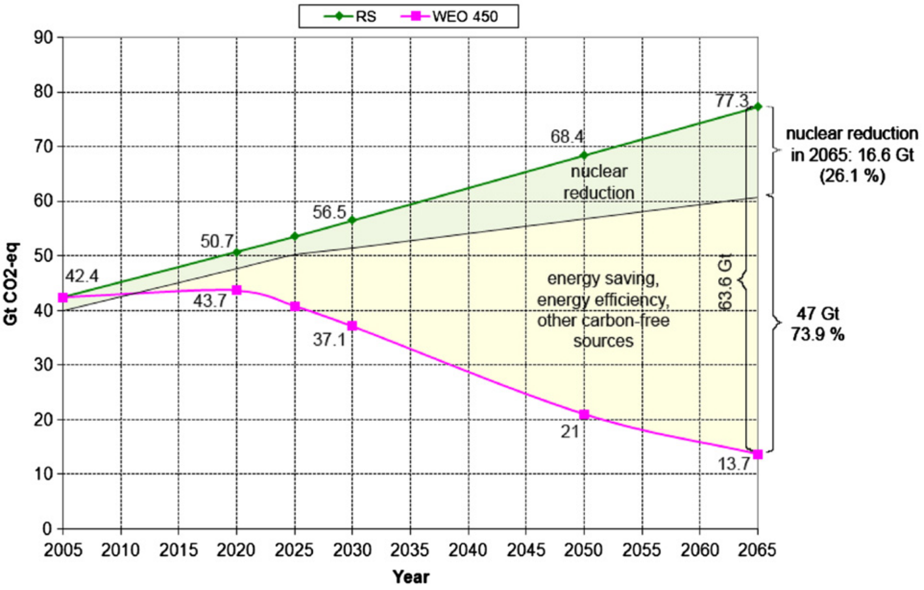

Fig. 4. Emission reduction by nuclear build-up (intermediate Scenario 4) in $GtCO_2$. The upper and bottom curves are the total anthropogenic emissions according to the WEO 2009 Reference Scenario and WEO 450 Scenario. The 2065 values are extrapolated from predictions up to 2050.

to the WEO 2009 carbon emission prediction. The production of nuclear energy by 2195 GW of NPP would amount to 17,305 TWh. As the NPP replaced CPP, using the coal appropriate figure for CO_2 emission per unit electricity of 0.960 kg/kWh we obtained an emission saving of 16.6 $GtCO_2$ in 2065. To assess the impact of this emission saving, it is compared to 2065 extrapolations of GHG emissions by Reference Scenario and WEO 450 of WEO 2009. These extrapolations are 77.3 $GtCO_2$-eq and 13.7 $GtCO_2$-eq, respectively, with a reduction of 63.6 $GtCO_2$ required to come down from the Reference Scenario to the WEO 450 Scenario. The nuclear reduction by 16.6 Gt CO_2 represents 26.1% of this requirement (as shown in Fig. 4). This is still a very significant contribution to the reduction of carbon emission, achievable without reprocessing nuclear fuel, and with uranium consumption well within the 2008 estimates, as evident in Table 4.

8. General discussion

8.1. Techno-economic aspects of nuclear build-ups

Nuclear build-ups mean, of course, large investment costs but investments in energy production are basic and unavoidable.[8] In the years 2010–2030, the 450 scenario would require 10.5 trillion

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[8] In the WEO 2009 Reference Scenario, total cumulative investment in the energy-supply infrastructure during the 2008–2030 period would amount to 25.5 trillion USD, of which 13.6 trillion would be in the power sector. Nuclear build-up during the 2025–2065 period may require some 12–15 trillion USD and reduce CO_2 emission by 25.2 $GtCO_2$. This can be compared to additional investment in the WEO 450 Scenario of 10.5 trillion for the 2008–2030 period, affecting emission reduction amounting to 19.4 $GtCO_2$. The standardization and industrial production of nuclear components could significantly reduce the unit costs of nuclear build-up.

dollars more investment in energy infrastructure and energy-related capital stock than the Reference Scenario. This figure would be significantly offset by the economic, health and energy security benefits plus energy saving in transport, building and industry estimated at 8.6 trillion US dollars for the same 2010–2030 period (IEA, 2009, p.47). The serial production and standardized designs of nuclear power stations should and must reduce the specific investment costs. When nuclear power plants replace the retired coal power plants, investment cost differentials are relevant and likely to narrow with the new generation of nuclear power plants. These costs also have to be judged by the value of the climate change avoided. With a higher share, nuclear energy could enter transport, an important and large sector of energy consumption and carbon emission. This could be achieved by providing electricity supply to electric cars, which may dominate in a few decades,[9] with clear environmental benefits.

Although more attractive from the point of view of carbon emission reduction, the linear growth Strategy 3 would require an annual reactor construction rate at the level of about 72 GW from the first year of nuclear build-up, 2025. However, under serious circumstances, international cooperation in the specialized serial production of components for a few standardized reactor types could ease the task.

For comparison, the world automobile industry annually produces about 75 million cars and light trucks. It could be debated whether this is a smaller undertaking than producing some 70 or fewer nuclear reactors. In the 1980–1990 period, some 200 GW of nuclear power were put into operation, with the maximum annual rate at about 30 GW. Of course, the recovery and reactivation of the nuclear industry would have to start very soon.[10] The Manhattan Project of more than 60 years ago shows what can be done when scientific and industrial knowledge, political will, and a sense of purpose and urgency work together. Widespread understanding that climate disaster is unavoidable without action could create the required political will for a new Manhattan.

The political, social, and environmental aspects are also important for wider deployment of nuclear power plant besides the techno-economic aspects. Clear and consistent government policy support is an essential for a successful nuclear program. Gaining greater public acceptance of nuclear power will also be the key to a rapid expansion of nuclear energy. Although the public recognition of the benefits of nuclear energy is increased in recent years due to concerns about security of supply and the threat of global climate change, further public support could be built through involvement of the public in the policy-making process. Our results showing that reprocessing of spent fuel can be postponed by several decades would contribute to public acceptance. The nuclear power is a mature low-carbon technology that meets environmental objectives. Even solutions of radioactive waste disposal are at an advanced stage of technological development. In a recent document by International Energy Agency and Nuclear Energy Agency (IEA-NEA, 2010) that proposes intensification of nuclear development with a target of 1200 GW by 2050, wide spectrum of prerequisites: political, industrial, educational, financial, and others are outlined. Proposed target, considered to low by WNA, is close to our strategy of replacing all retiring non-CCS coal plants after 2025.

8.2. Nuclear energy after 2065; options

As we have shown, uranium resources with once-through fuel technology would make a very substantial nuclear contribution to carbon-free energy production possible. However, recalling the assumptions of the study, i.e., the consumption of uranium resources by 2065, we now discuss the question of what would happen after the year 2065 should the maximum possible build-up be applied. Will the production of nuclear energy stop at that year? There are a number of answers to this dilemma but it would be preposterous to predict which one will be realized in 50 years from now, without knowledge of the developments bound to take place in the intervening decades. Let us briefly list of some of them.

First, the exhaustion year 2065 assumes the present estimates of uranium resources, including those currently classified as Prognosticated and Speculative. Therefore, the task for the next 50 years is to turn those categories into the category of Identified Resources. The task is less formidable if we note that resource estimates have grown over the years and will probably not freeze at 2008 values. By 2060 or so, uranium from phosphates could be available at an acceptable cost. Should the cost of uranium extracted from seawater be available at the previously cited price of 250 USD/kg U in 50 years from now, it would at least be acceptable for fast breeders. It should also be recalled that exhaustion by 2065 ensues for maximum growth scenarios. Lower growth rates that still satisfy climate requirements would consume correspondingly lower quantities of uranium.

Second, for both Scenarios 2 and 3, close to 13,000 t of Pu would be contained in the spent fuel in 40 years of nuclear build-up between 2025 and 2065, as can be seen in Tables 2 and 3, enough for some 15 years of fuelling 3330 GW of nuclear reactors with plutonium, replacing U^{235}.[11] An alternative use of the plutonium would be for starting fast breeders. In either case, no fresh uranium would be needed. Merely by recycling plutonium, we could maintain nuclear power at the 3330 GW level to the year 2080, which is long enough to give a sporting chance for CCS and fusion to make a serious contribution to carbon-free energy. Should they both fail, about 8000 t of additional Pu could be extracted from the additional spent fuel from the 15 years of operation of the fleet of 3330 GW of nuclear power from 2065 up to the year 2080. The situation would be less favorable for the exponential Scenario 2, reaching 4447 GW by 2065, since the amount of plutonium in spent fuel would be the same for both strategies. Therefore, plutonium would cover about 10 years of the operation of 4447 GW of nuclear power.

Third, once fuel reprocessing is introduced, thorium fuel cycles can be used, thereby opening the way for the use of large thorium resources, as well.

Fourth, a possibility on the horizon is the production of fissile nuclides by spallation reactions with particle accelerators. This has been studied from the early days of nuclear development (Steinberg et al., 1983). The required technical extension of current accelerators should not pose too great a problem by those years. Alternatively, neutrons from fusion devices could be used for the production of fissile nuclides.

There are clearly sufficient technical possibilities for well founded optimism that the operation of nuclear reactors could be sustained after the “exhaustion year” 2065. Nonetheless, we shall

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[9] The impact of electric cars can be illustrated by a UK Transport Commission study which estimates a 16% increase in electricity consumption if there were a transition to battery-driven cars. The US Energy Power Research Institute estimates a 9% increase in energy consumption should 60% of the cars in US use electric drive. The European utility Areva has calculated that if 10% of the cars in France were electric, this would increase base-load demand by more than 6000 MWe.

[10] See the relevant warning in the MIT EI (2009) update of the 2003 study, The Future of Nuclear Power.

[11] All the reactors that will be in operation in the year 2065 can use a full core of MOX fuel (WNA, 2010), since these reactors are of Generation 3 or higher.

not indulge in guesswork about future technical advances and consequently abstain from predicting uranium requirements after the exhaustion year. Finally, 2065 would be the "exhaustion year" in the case of maximum possible build-up, such as Scenarios 2 and 3. Slower build-ups, such as Scenario 4, would postpone the exhaustion year correspondingly.

8.3. *Nuclear energy after 2065, plutonium use safety*

Should a share of nuclear contribution after the draining of uranium resources with once-through fuel use by the year 2065 be maintained by plutonium recycle in thermal reactors or by the introduction of breeder reactors, then up to five years before the exhaustion year, i.e., by about 2060, the large-scale reprocessing of spent fuel should begin in order to produce plutonium fuel in time. There would be up to 50 years to commercialize and introduce the required reprocessing and plutonium fuel cycle technologies and create the secure and controlled proliferation-safe environment needed for their application. Considering the magnitude of the task, it is by no means a period too long for comfort. Many hundreds of tons of plutonium would be contained in the fuel that would go every year to the 3500 GW or more of nuclear power stations located in an increased number of countries. Diversion on the level of a few kg of Pu is not acceptable. From the current perspective, it is difficult to speculate on future technical and other measures to ensure proliferation safety. However, here the key words are "from the current perspective." After the era of the big wars of the past century, we still live in the era of confrontations, as witnessed by decades of futile negotiations on nuclear disarmament and disappointingly slow progress in the removal of nuclear weapons after the end of the Cold War, with the effect of turning nuclear weapons into an attractive status symbol to some non-nuclear weapon countries, "a ticket to the high table of international politics." Should we extend such international relationships into the future, we may indeed question whether the obtained time window of about 50 years is sufficient for the construction and safe operation of about 3500 GW of nuclear reactors and for the simultaneous creation of conditions for the nuclear proliferation-safe introduction of large-scale reprocessing after 2060 or thereabouts. Some form of international fuel service will be needed, as it is almost certain that proliferation safety could not be achieved with the operation of an increased number of national enrichment and reprocessing installations. The old Baruch proposal[12] of 1946 could inspire new solutions (Baker, 1958). Highly efficient and generally accepted nuclear safety inspection to control installations, fuel storage and transport is one of the more obvious requirements should large-scale plutonium use be an option after 2065. The collocation of reactors and fuel cycle installations at a small number of internationally controlled sites would be conducive to security. However, it is difficult to view the success of technical measures alone without parallel progress in nuclear disarmament. The ambitions of some countries to join the exclusive "nuclear club" will only be terminated by the final dissolution of the club.[13]

If not from more positive motives, then faced with the certainty of climate disaster, humanity could turn from confrontation into cooperation and the problems presently paralyzed by conflicting interests could be resolved. There are some grounds for optimism from recent history, when reason prevailed over the deadly dangerous Mutually Assured Destruction (MAD) "defense" postures.

9. Summary and conclusion

In this study, we have investigated the potential of nuclear fission energy, under the constraints of estimated uranium resources and the use of once-through nuclear technology, to make an essential and timely contribution to the reduction of CO_2 emission. Selecting the year 2065 for the completion of nuclear build-up, we find two strategies starting in 2025 that would exhaust uranium resources by then. One is exponentially growing by an annual rate of 5.3%. The other is growing linearly by 71.8 GW/year. The nuclear power reached by 2065 is 4447 GW for the exponential strategy and 3330 GW for the linear strategy, while the cumulative nuclear energy produced and carbon emission savings are the same in both strategies. In the exponential strategy, a larger part of the energy is produced in the later years of the build-up period. Preference is afforded to the linear strategy because investments would be lower and CO_2 emission reduction takes place earlier. The nuclear contribution develops from 2025, after the period when the main burden of emission reduction could be borne by earlier applicable energy-saving and efficiency measures. The upper limits of nuclear build-up obtained under the stated constraint are sufficient for the resolution of the climate problem. The nuclear emission saving of 25.2 $GtCO_2$ to be achieved in 2065 would contribute 39.6% of the GHG emission reduction of 63.6 $GtCO_2$ needed to bring the WEO 2009 Reference Scenario for the global estimate of anthropogenic greenhouse-gas emission for 2065 from 77.3 $GtCO_2$-eq down to the WEO 450 Scenario for the total anthropogenic emission 2065 level of 13.7 $GtCO_2$-eq. After the nuclear contribution of 39.6%, reduction of 38.4 $GtCO_2$, i.e., 60.4%, would remain for other measures of carbon emission abatement. Smaller nuclear shares could also be sufficient, depending on the contributions from other carbon-free energy sources, but that would require more detailed assessment of their development. To illustrate the possibilities, we also analyzed an intermediate strategy defined as the replacement by 2065 of all non-CCS CPP operating in 2025. With a nuclear build-up reaching 2195 GW by 2065, emission reduction would reach 26.1% of the required value. The main result of both the high and intermediate strategies is that using only once-through fuel technology and the present estimate of uranium resources, an essential contribution of carbon-free energy to total world energy production can be achieved. We consider this an important element for political decisions on future energy strategies and for public acceptance of nuclear energy.

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[12] The US Government proposal to the UN known as the Baruch Plan was presented by Bernard Baruch, the US delegate to the UN Atomic Energy Commission, on June 14, 1946. It was essentially a follow-up of the Washington Declaration of November 15, 1945 by the President of the United States and the Prime Ministers of Britain and Canada for the elimination of atomic weapons and only the peaceful use of nuclear energy. However the Baruch Plan was "chiefly the work of Dr. Oppenheimer's bold and generous heart and brain"(Baker, 1958). The plan was backed and supported by groups of outstanding American scientists, who proposed the establishment of an UN agency for the peaceful use of nuclear energy, the International Atomic Development Authority, IADA. The IADA would have had complete control over all fuel cycle activities, manufacturing nuclear fuel and leasing it to national atomic energy authorities that would operate reactors licensed by the IADA. Unfortunately, the Soviet Union was already in the process of making its own atomic bomb and rejected the proposal with great hostility. Instead of creating an organization for the safe use of nuclear energy, which would also have added strength to the UN, at that unhappy moment of history the world was turned toward the nuclear arms race and cold war.

[13] Steven E. Miller and Scott D. Sagan in AAAS Dedalus 2009: "If nuclear weapons remain the currency of the realm, if they are the ticket to the high table of international politics, if they are believed to confer enormous diplomatic and security benefits, if the existing NWS insist on the necessity to retain their nuclear weapons for the indefinite future, then it will be very difficult over the long run to make the case that for all other states nuclear weapons are unnecessary and undesirable."

As maximum nuclear build-up would exhaust the currently estimated uranium resources by 2065, we have discussed various options after 2065. Extension of the uranium resources could make the use of once-through technology possible after 2065. Should the option be plutonium use in thermal or breeder reactors, with an annual use of plutonium at the level of many hundreds of tons, the large-scale reprocessing of spent nuclear fuel should start soon after about 2060 in order to produce plutonium and plutonium fuel for use from 2065 and afterwards. Plutonium use on such a vast scale cannot be imagined without internationalizing nuclear fuel cycle installations and far more efficient inspections. A much more demanding approach to proliferation safety would be required. We show that a nuclear build-up can make an essential contribution to carbon emission reduction, while postponing the introduction of large-scale reprocessing by about 50 years. During that period, plutonium would be safely stored in heavy spent-fuel casks, in accordance with accepted practice. These precious 50 years, given an understanding of what can be gained and lost, should be sufficient for the creation of the international institutions required for the safe use of plutonium after 2065, if plutonium use becomes necessary. A dose of optimism comes from the belief that in a world faced with a common climate threat, the current negative and confrontational political environment will be replaced by the realization that "only united we stand." It can be done: adversaries of the two bloodiest wars of the past century are now partners in the European Community.

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